UTILIZATION OF WATER HYACINTH AND SUGARCANE BAGASSE FIBRES FOR THE DEVELOPMENT OF GREEN TEXTILE MATERIALS

Synopsis

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1. INTRODUCTION

In the quest for sustainable development, the textile industry is adopting innovative approaches throughout its supply chain to reduce its environmental impact. A key element in this endeavour is the transition to sustainable and eco-friendly raw materials, along with the adoption of energy-efficient and minimal-polluting processes. The ecological footprint of textile products can be greatly improved by incorporating such materials, significantly enhancing the overall sustainability of the industry. By utilizing renewable sources like plant fibres—such as bast and leaf fibres, including weeds and plant waste—processed through environmentally friendly methods, the industry can minimize its ecological impact. This approach ensures that textiles are produced with minimal environmental harm and can be disposed of in an environmentally responsible manner, thereby contributing substantially to sustainability goals.

In recent years, there has been a growing recognition of the importance of recycling across various sectors. However, there has been relatively little emphasis on recycling waste fibres and utilizing them for the development of non-woven and composite materials. Thus, adopting sustainable practices such as utilizing eco-friendly fibres, agricultural waste and aqueous waste aligns with global objectives to combat climate change and protect biodiversity. These fibres require less energy for extraction and processing, thereby reducing greenhouse gas emissions. They contribute to a more sustainable future and promote the development of valuable new materials.

The present study aims to utilize water hyacinth, an aqueous weed, and sugarcane bagasse, an agricultural waste, to develop sustainable textile materials in the form of non-wovens composites and bioplastics. These fibres are abundantly available and can be processed using eco-friendly methods, thereby minimizing environmental impact.

1.1. WATER HYACINTH (EICHHORNIA CRASSIPES)

Eichhornia crassipes, also referred to as the water hyacinth, is a free-floating aquatic plant, belonging to the family Pontederiaceae. It is regarded as one of the top ten worst weeds in the world and is distinguished by its quick growth rates, wide spreading ability, prolific and quick reproductive output, and resistance to a variety of environmental conditions. It can double its population in 6–18 days and, in high-nutrient areas, in as little as 5 days. It is considered one of the most productive plants on earth,

producing more than 200 tons of dry matter per hectare annually.

Water hyacinth is a native Brazilian plant that was introduced in India as an ornamental plant in the botanical garden in Bengal. A field study done by Narayanan et al. (2006) indicates the presence of Water Hyacinth in the majority of states from India. These include Kerala, West Bengal, Madhya Pradesh, Uttar Pradesh, Himachal Pradesh, Punjab Andhra Pradesh and Manipur are polluted with water hyacinth growth.

Water hyacinth poses significant issues, including physical problems like choking water bodies, hindering fishing and boating activities, and reducing water movement due to dense mats. Environmentally, it obstructs photosynthesis, lowers oxygen levels, and disrupts aquatic ecosystems, leading to reduced biological diversity and habitat alteration. Economically, controlling water hyacinth incurs substantial costs. While efforts have reduced these expenses through maintenance control, the plant still presents ongoing challenges to water management and conservation efforts.

1.1.1. Physical Structure of Water Hyacinth

Water hyacinth, scientifically known as Eichhornia crassipes, presents a distinctive floating structure. Its leaves are dark green, rounded, and sturdy, measuring between 10 to 20 centimetres across, and are affixed to spongy stalks. The flowers of this plant range from lavender to pink in colour, are approximately 1.5 to 2.25 inches in both length and width and are supported by a single spike on an upright stalk. (Figure: 1.1).

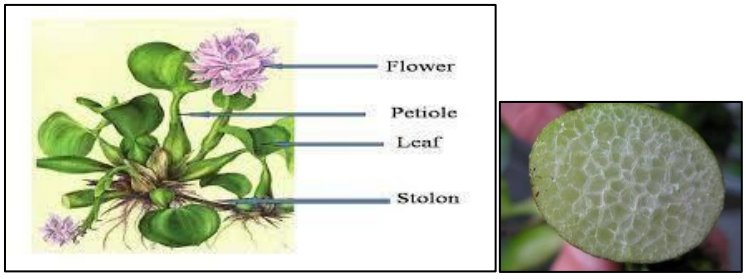

Figure 1.1 Physical Structure of Water Hyacinth Plant

1.1.2. Chemical Composition of Water Hyacinth

The chemical composition of water hyacinth includes carbon, oxygen, sodium, magnesium, aluminium, zirconium, chlorine, potassium, calcium, silicon, titanium, and iron. The biomass also contains 36% hemicellulose, 21% cellulose, 7% lignin, 4.9% moisture, 61.2% volatile matter, 13.8% fixed carbon,

and 20.1% ash (Omondi et al., 2019).

1.1.3 Applications of Water Hyacinth Fibres

Water hyacinth (Eichhornia crassipes), often viewed as an invasive weed, has valuable applications in sustainable practices and local industries. The House and Building Research Institute in Dhaka utilizes it to produce fibre board, providing a locally sourced construction material that addresses the plant's overgrowth in waterways (Rahman et al., 2021).

1.2. SUGARCANE BAGASSE (GRAMINEAE SACCHARUM OFFICINARUM L.)

Sugarcane (Saccharum officinarum) bagasse (SCB) (Figure 1.2). is a biomass of agricultural waste obtained from sugarcane processing that has been found in abundance globally. Bagasse is the fibrous residue remaining after sugarcane stalks are crushed. In essence, bagasse is considered a waste product, necessitating additional disposal costs due to its annual production of roughly 100 million tons. **(**Uddin et al., 2010, Asagekar & Joshi, 2014).

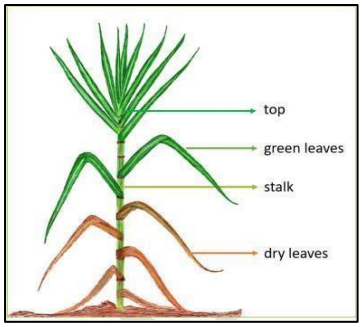

Figure 1.2 Sugar cane stalk

1.2.1. Physical Structure of Sugarcane Bagasse

Following the extraction of the juice, crushed sugarcane is used to create sugarcane bagasse, a fibrous substance. Both the inner pith and the outer rind make up the stalk. The physical structure of sugarcane bagasse consists of fibres with an average length of 1.7mm, ranging from 0.8mm to 2.8mm. These fibres have an average width of 20µm, varying from 10µm to 34µm. (Nunes et al., 2020)

1.2.2. Chemical composition of Sugarcane Bagasse

Bagasse has approximately a cellulose content of 50% hemicellulose in 25% and lignin in about 25%. cellulose exhibits a crystalline structure, with its crystallinity ranging from about 50–90% depending on the cellulose source, whereas hemicellulose possesses an amorphous structure containing xylose,

glucose, and other elements. (Mahmud & Anannya, 2021).

1.2.3. Applications of Sugarcane Bagasse Fibres

Sugarcane bagasse (SCB) stands out as a readily available biomass with diverse potential applications. SCB serves as a versatile feedstock to produce different biofuels including bioethanol, biomethane, biohydrogen, and bio-butanol, offering sustainable alternatives to traditional fossil fuels. Beyond its role in energy production, SCB proves valuable as a sustainable raw material for creating adsorbents, briquettes, ceramics, concrete, and composites.

1.3. HARNESSING CELLULOSE FROM TEXTILE WASTE

In today's textile industry, there's a growing emphasis on repurposing waste materials to create sustainable solutions for environmental and economic benefits. Cellulose, a polysaccharide composed of glucose subunits, plays a vital role in plant structure and strength, making it an essential biopolymer. Its biodegradability, biocompatibility, and excellent thermal-mechanical properties make it ideal for various applications such as papermaking and food packaging (Habibi et al., 2010). While wood was traditionally the primary source of cellulose, recent research has focused on extracting cellulose from agricultural byproducts and textile wastes, which are abundant and cost-effective raw materials.

1.4. NATURAL FIBRE-BASED NONWOVENS

Nonwovens encompass a broad spectrum of applications, ranging from paper to textiles, making them a versatile material category. This innovative approach developed nearly a century ago, involves forming fibres into the fabric using the most direct and efficient methods available. Natural fibre-based nonwoven materials, derived from renewable plant sources like cotton, jute, hemp, bamboo, sisal, or wool, offer a sustainable and environmentally friendly alternative to traditional synthetic fibres. These materials boast excellent breathability, moisture absorption, and biodegradability. Produced using techniques such as needle punching, wet laying, or air laying, they have diverse applications across industries, from hygiene products to automotive and construction materials.

1.5. BIOPLASTICS

Bioplastics represent a revolutionary category of plastics crafted from renewable resources and engineered to be biodegradable, marking a significant stride towards sustainability. Currently, the production of entirely bio-based bioplastics is scaling up, reaching approximately 2 million tonnes

annually. By harnessing biological processes and their intricate mechanisms, bioplastics offer a multifaceted solution to pressing environmental challenges. Their biodegradability ensures that they break down naturally, reducing the burden of plastic pollution on ecosystems and marine life. However, the following are the most common bioplastics being used in the present day include starch, cellulose and protein-based bioplastics or are derived from aliphatic polyesters or bio-derived polyethylene.

1.6. SIGNIFICANCE OF THE STUDY

In today's era, there's a noticeable shift towards prioritizing sustainability in research endeavours, aimed at preserving the ecosystem. The 21st century has marked a period of remarkable transformation in textile research and innovation, characterized by the integration of sustainability principles with advanced materials, opening unprecedented avenues. Traditional textile materials, often derived from finite resources, present significant environmental challenges, prompting the need for exploration into sustainable fibres and composites.

Natural fibres, derived from various plant sources, have long been indispensable for human needs. These eco-friendly materials comprise essential components such as cellulose, hemicelluloses, lignin, pectin, and waxes. In response to escalating environmental concerns associated with synthetic fibres, derived from petroleum sources, there's been a heightened exploration and utilization of natural fibres and textile waste. Water hyacinth plants pose a significant threat to biodiversity due to their congested growth and rapid spread). These cleanup operations incur significant expenses, amounting to nearly 10 lakhs per year (The Times of India, Feb 24, 2017). Likewise, substantial quantities of agricultural waste in the form of sugarcane bagasse, is generated by crushing and milling of sugarcane stalks which consist of moist cellulosic fibres bound together with lignin compounds. However, due to inadequate waste disposal practices, over 50 tons per day of sugarcane waste are either dumped along roadsides and railway tracks or burned to fuel boilers in sugar mills. In this context, exploring the potential of water hyacinth fibres and sugarcane bagasse, both rich in cellulose and readily available as aqueous and agricultural waste, offers a promising avenue for sustainable textile applications.

The current study attempts to develop nonwoven composites and bioplastics from these cellulose-based textile wastes for their suitability in addressing specific environmental issues. The research into green textiles from water hyacinth and bagasse fibres not only aligns seamlessly with the global sustainability

movement but also embodies the principles of a circular economy. By addressing environmental challenges and promoting innovation, it promotes a responsible approach to material production and consumption. The outcomes of this research hold wide-ranging implications, benefiting industries, communities, and the planet's overall health. They signify a shift towards sustainable practices that not only reduce environmental impact but also foster economic growth and social wellbeing.

1.7. STATEMENT OF THE PROBLEM

Based on the above lines, the following statement of the problem is proposed-

UTILIZATION OF WATER HYACINTH AND SUGARCANE BAGASSE FIBRES FOR THE DEVELOPMENT OF GREEN TEXTILE MATERIALS

1.8. OBJECTIVES OF THE STUDY

- To extract fibres from water hyacinth and sugarcane bagasse using various extraction methods and compare their fibre yields.
- To characterize the physical, chemical, and mechanical properties of water hyacinth and sugarcane bagasse fibres and compare them with other novel natural fibres.
- To isolate cellulose from water hyacinth and sugarcane bagasse using different processes and compare the cellulose yields.
- To develop non-woven bio-composites from the extracted fibres, and evaluate their mechanical, thermal and environmental properties for sustainable applications.
- To create bioplastics from the cellulose isolated from water hyacinth and sugarcane bagasse and conduct standardized tests to assess the properties of the produced bioplastics.

1.9. OPERATIONAL DEFINITIONS

- **Sustainable:** In 1987, the United Nations Brundtland Commission defined sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.” ."
- **Non-woven:** Nonwoven fabrics are flat, porous sheets or web structures that are made directly from fibres, from molten plastics, or from plastic films by entangling fibres or filaments mechanically, thermally, or chemically. (Kilinc, 2013)
- **Bioplastics:** Bioplastics are polymers made from renewable resources that can be naturally recycled

through biological processes. Thus they have been suggested as a greener and sustainable solution to address the growing demands and pollution issues of petroleum-based plastics (Dietrich, Dumont, Del Rio, & Orsat, 2017)

1.10. DELIMITATIONS OF THE STUDY

- The proposed study will be restricted to only two eco-friendly fibres viz. Water hyacinth and Sugarcane Bagasse.
- The proposed study will be restricted to developing non-woven by wet laid process only.
- The proposed study will be restricted to developing Bioplastics by hand layup method only.

2.0. REVIEW OF LITERATURE

A Review of Literature (ROL) is a methodical assessment of existing scholarly works, including research articles and books, focused on a specific topic or research question. It involves critically analysing and summarizing the findings, methodologies, and theoretical frameworks of previous studies to gain a comprehensive understanding of the current state of knowledge in the field.

2.1. Textile Fibres

Textile fibres serve as the foundational components for both finished and semi-finished textile goods. Textile fibres, encompassing natural, synthetic, and high-performance types, play a vital role in creating woven, knitted, and composite structures used in various automobile components. The increasing demand has led to the utilization of earlier neglected plant fibres such as coir, bamboo, bagasse, and pineapple (Jawaid & Abdul Khalil, 2011). Useful fibres have been obtained from various parts of plants, including leaves, stems (bast fibres), fruits, and seeds. While fibres from fruits and seeds are relatively short, those from stems and leaves are longer.

2.2. Natural Fibres and their Classification

Saravana Bavan (2010) defines natural fibres as hair-like structures derived from crops, animals, or minerals. Natural fibres often contain cellulose, lignin, and hemicellulose (Ashok et al., 2015. Natural fibres consist of three primary components: lignin, cellulose, and hemicellulose, with the proportions of each varying depending on the type of natural Fibre.

2.3. Lignocellulosic Fibres

Lignocellulosic fibres are abundant globally, with their production estimated at 10–50 billion tons per

year, accounting for approximately 50% of the biomass (Caffall, 2009). The composition of plant fibres—comprising cellulose, hemicelluloses, and lignin varies based on position, species, and environmental conditions.

2.4. Water Hyacinth Plant (Eichhornia Crassipes)

Water hyacinth (Eichhornia crassipes) is a rapidly growing, free-floating perennial aquatic plant (Sotolu, 2013). It reproduces swiftly through vegetative means, with a daily weight gain of 4.8% and doubling in size every 11-15 days, according to field observations by various authors. Consequently, water hyacinth poses significant threats to biodiversity and obstructs water transportation, canal irrigation, and power generation by blocking waterways. Various measures have been implemented to control its growth, and research efforts are ongoing to eradicate the weed.

2.4.1. Characteristics of Water Hyacinth

Water Hyacinth stems have long and uniform fibres, making them ideal for advanced textile production. According to Supri and Ismail (2010), these fibres are mechanically robust due to their high cellulose content. The chemical makeup of WH fibre is roughly 60% cellulose, 8% hemicellulose, and 17% lignin. Research suggests that these materials offer numerous benefits, including high mechanical strength (B. M & K, 2017), non-corrosive properties (Jirawat Tanasomkul et al. 2021), low density (Salas-Ruiz and Barbero-Barrera 2019), high thermal insulation, antibacterial properties, low cost, availability, and high absorbency (Abral et al. 2018).

2.4.2. Applications of Water Hyacinth Fibres

Sandeep et al. (2023) investigated the biosorption of basic fuchsin dye using different quantities of dried and powdered water hyacinth biomass. Msemwa et al. (2022) demonstrated the utilization of water hyacinth for phytoremediation of textile effluents. Own et al. (2022) developed and characterized water hyacinth fibre thermoset epoxy (WHE) composites. Pratma et al. (2020) pioneered the use of water hyacinth biochar-based composites for sound absorption, while Chaosri et al. (2020) extracted cellulose from water hyacinth for the preparation of cellulose/silk fibroin composite films.

2.5. Sugarcane Bagasse (Gramineae Saccharum Officinarum L.)

Sugarcane (Saccharum officinarum) is extensively cultivated in tropical regions, with global production reaching approximately 1.84 billion tons in 2017 (FAOSTAT,2019). While primarily processed in sugar

and alcohol mills, a significant portion of sugarcane cannot be fully utilized by these facilities, resulting in the generation of approximately 30% pulpy fibrous residue known as bagasse (Michel et al., 2013).

2.5.1. Characteristics of Sugarcane Bagasse Fibre

Sugarcane bagasse fibre demonstrates various physical attributes, characterized by its fibrous structure, length, diameter, and surface morphology. Bagasse fibres generally vary in length from a few millimeters to several centimetres, while their diameters typically fall within the range of 10 to 40 micrometres (Alves et al., 2019). Soni and Patel (2017) investigated the physical characteristics of bagasse fibre, including dimensions, density, and surface morphology, unveiling its inherent structural properties and versatility for diverse applications**.**

2.5.2. Applications of Sugarcane Bagasse Fibre

Sugarcane bagasse, a fibrous byproduct of sugarcane processing, has attracted considerable interest for its potential applications in the textile industry because of its abundance, renewability, and biodegradable properties. Bagasse-based composites have been developed for various textile applications, including non-woven fabrics, geotextiles, and reinforcement materials, offering improved biodegradability, reduced environmental impact, and cost-effectiveness (Gañán et al., 2017). In recent studies, several researchers have utilized nanocellulose to produce eco-friendly composite materials. Gadheri et al. (2014) extracted nanocellulose from sugarcane bagasse and used it to reinforce cellulose film, creating a sustainable material for food packaging.

2.6. Natural Fibre Based Non-Wovens

Nonwoven textiles are made directly from Fibres without the need for intermediate activities like yarn production. Ahmed et al. (2019) provided a detailed discussion on the classification of nonwoven materials based on web formation methods, which include spun-bond, melt-blown, needle-punch, air-laid, and wet-laid processes. Natural fibres have numerous benefits, including excellent thermal, acoustic, and electrical insulation properties, high mechanical strength, low specific gravity, low carbon emissions, low cost, easy processing, and recyclable properties. Supri and Ismail (2010) report that Water Hyacinth fibres are mechanically robust due to their high cellulose content. Water Hyacinth fibres contain 60% cellulose, 8% hemicellulose, and 17% lignin. Research suggests that these materials offer numerous benefits, including high mechanical strength (M & K, 2017)., non-corrosive properties, low

density **(**Salas-Ruiz and Barbero-Barrera 2019**),** high thermal insulation, antibacterial properties, low cost, availability, and high absorbency **(**Abral et al. 2018). A study by Miller, (2021) demonstrated the use of aquatic weed like water hyacinth for acoustic purposes by turning it into Fibres and mixing it with natural textile fibres like Sansevieria, Banana, and Hemp.

2.7. BIOPLASTICS

Plastics are typically created from petrochemicals, although there is a growing interest in producing "bioplastics" from renewable resources as an alternative material. Bioplastics are classified as either biodegradable or non-biodegradable. Biodegradable bioplastics vary in rate and method of breakdown, contributing to their diversity. (Jabeen et al., 2015). Researchers have investigated diverse cellulose sources, ranging from wood pulp to agricultural leftovers and microbial cellulose, for the production of bioplastics (Bakare et al., 2015).

Kusumaningrum et al. (2023) explored the utilization of jicama starch as the primary component for bioplastic fabrication. Their findings revealed that optimizing the bioplastic degradation ability was achievable through adjustments in the quantities of glycerol and chitosan. Halim et al. (2023) identified the optimal conditions for incorporating chitosan and sorbitol and evaluated their impact on the quality of bioplastic production using the solution casting method. Jhon & Haryanto (2022) synthesized a biodegradable plastic using corn starch, with chitosan and calcium silicate as fillers and glycerol as a plasticizer.

3.0 METHODOLOGY

A methodological analysis of the study problem is methodical and rational. It is a science that investigates issues to implement scientific answers. This research aims to investigate the feasibility of extracting fibres from Water Hyacinth petioles and Sugarcane Bagasse to develop sustainable textile materials, including non-wovens composites and bioplastics. The study will be broadly classified into four phases as shown in Fig: 3.1:

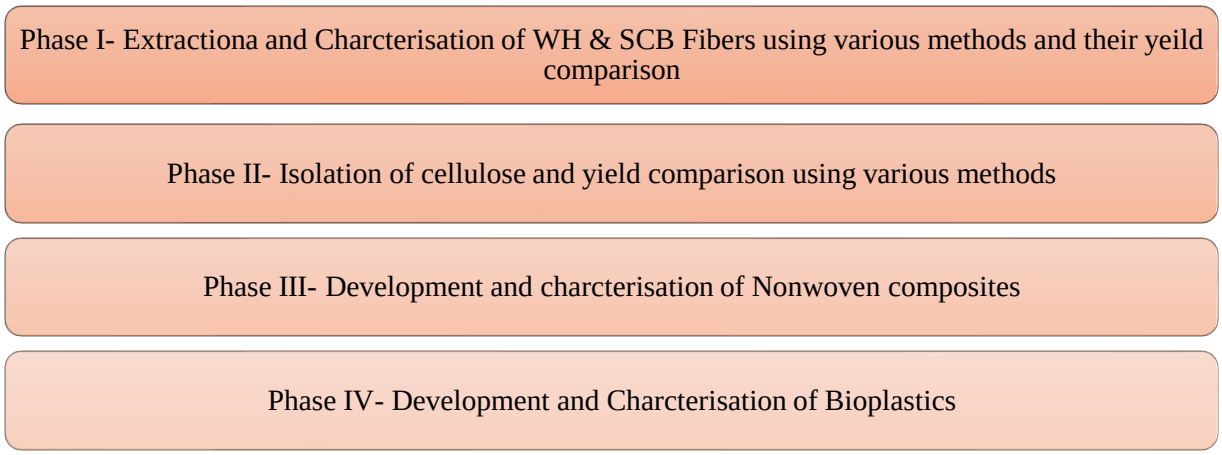
Phase I- Extractiona and Charcterisation of WH & SCB Fibers using various methods and their yeild comparison
Phase II- Isolation of cellulose and yield comparison using various methods
Phase III- Development and charcterisation of Nonwoven composites
Phase IV- Development and Charcterisation of Bioplastics

Figure 3.1 Phases of the study

3.1. Fibre Extraction

Water hyacinth (Eichhornia crassipes) will be collected from ponds, lakes and reservoirs. Sugarcane waste will be sourced from the local Sugar Cane juice sellers.

3.1.1. Water Hyacinth Fibre Extraction

Water Hyacinth fibres will be extracted using different methods to compare the yield and physical, mechanical and chemical properties. The methods are listed below:

- Mechanical Extraction
- Retting Extraction
- Chemical Extraction
- Enzymatic Extraction

3.1.2. Sugarcane Fibre extraction

Sugarcane fibres will be extracted using different methods to compare the yield and physical, mechanical and chemical properties. The methods are listed below:

- Retting Extraction
- Chemical Extraction
- Enzymatic Extraction

3.1.3. Characterization of extracted Fibres

The extracted fibres from water hyacinth and sugarcane will be evaluated for their physical, chemical, and mechanical properties to determine their suitability for textile materials. The assessment will focus on several criteria including chemical composition, linear density, tenacity, breaking energy, bending

rigidity, tensile strength, tensile modulus, FTIR analysis, yield percentage, and flexural properties.

3.2. Isolation of Cellulose from Water Hyacinth and Sugarcane Bagasse

To isolate cellulose from both water hyacinth and sugarcane bagasse, the fibres will first be cleaned, dried, and ground into a fine powder. Each type of fibre will then undergo a series of chemical treatments to remove non-cellulosic components, utilizing variations of sodium hydroxide, sodium hypochlorite, and other agents such as hydrogen peroxide and acetic acid. These methods aim to maximize cellulose purity and yield, ensuring the Fibres are suitable for textile applications.

3.2.1. Isolation of Cellulose from Water Hyacinth

- Method 1: Sodium hydroxide, sodium chlorite, methanol, and ethanol.
- Method 2: Sodium hypochlorite, sodium hydroxide, and hydrochloric acid.
- Method 3: Hydrogen peroxide and sodium hydroxide.

3.2.2. Isolation of cellulose from Sugarcane Bagasse

- Method 1: Sodium Hydroxide and Sodium Hypochlorite.
- Method 2: Sodium Hydroxide, Sodium Chlorite and Acetic acid.
- Method 3: Sodium Hypochlorite and Sodium Hydroxide.

3.3. Nonwoven Fabrication from the Extracted Fibres

The fabrication of nonwovens from extracted fibres represents an innovative approach to utilizing abundant natural resources in sustainable materials engineering. These fibres, extracted from water hyacinth and sugarcane bagasse, both commonly considered waste materials, offer a promising avenue for creating nonwoven materials with diverse applications.

Table 3.1. Proposed ratios for blending of Fibres for developing Non-woven

Sample	Water Hyacinth fibres (%)	Bagasse fibre (%)
1.	60	40
2.	40	60
3.	50	50

3.3.1. Non-woven formation

The wet-laid web formation method, an adaptation of traditional papermaking, will be employed to produce nonwoven fabrics through a systematic, multi-step process. First, Fibres will be mixed with appropriate binders or matrices and suspended in water to form a fibre slurry. This slurry will then be

carefully deposited onto a moving wire screen or other porous surface, enabling an even distribution of fibres across the surface. Following this, the water will be drained, allowing the fibres to merge into a uniform sheet. The fibre web will then undergo consolidation to enhance its structural integrity, using mechanical, chemical, or thermal methods as needed. Finally, the web will be thoroughly dried to create a stable, nonwoven fabric with desired properties for various applications.

3.3.2. Development of Nonwoven Bio-composites

The hand lay-up method, an open-forming technique widely used in composite material production, is one of the oldest and simplest methods, especially well-suited for manufacturing large components. In this process, pre-formed nonwoven sheets will be manually placed into an open mold that has been prepared with a layer of resin. Using tools such as a trowel or roller, the resin will be carefully spread across the mold, ensuring that the fibres are fully saturated for optimal adhesion and uniformity.

3.3.3. Characterization of Developed Nonwoven Bio-Composites

Testing is a crucial step in the textile industry, encompassing everything from the selection of raw materials to processing and finishing. The developed nonwoven bio composites will be subjected to a variety of testing methodologies, including physical, mechanical, and thermal analyses. Moisture properties will also be examined using standardized procedures and specialized equipment. Key metrics for evaluation will include Fibre weight ratio, breaking strength, tensile strength, elongation, Izod impact strength, drop weight impact strength, differential scanning calorimetry (DSC), thermogravimetric analysis, and thermal conductivity.

3.4. Fabrication of Bioplastics

The development of bioplastics from cellulose will involve dissolving cellulose in distilled water and stirring it at room temperature to ensure an even dispersion. Sodium alginate, a natural thickening agent, will be added to enhance the bioplastic’s strength, flexibility, and moisture resistance. This cellulosealginate mixture will then be homogenized, poured into an acrylic mold, and dried at room temperature over 48 hours, allowing gradual water evaporation and solidification.

3.4.1. Characterization of Developed Bioplastics through Physical, Mechanical, Moisture, and Thermal Analyses

The bioplastic materials will undergo comprehensive evaluation using standardised procedures and specialized equipment across various testing methodologies, including Physical, Mechanical, and Thermal Analyses. Moisture properties will also be rigorously assessed. Key analyses will cover Thickness, Tensile Strength, Moisture Content and Regain, Water Solubility, Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), Scanning Electron Microscopy (SEM), Biodegradability, and Surface Activity. Each test will contribute to a detailed understanding of the bioplastic's properties and performance characteristics.

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